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THE M31 GLOBULAR CLUSTERS IN THE INFRARED

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ABSTRACT

We review the infrared observations, both photometric and spectroscopic, of the globular clusters of M31. As a preliminary step, we summarize the observations in the infrared of individual stars in galactic globular clusters, then the observations of the integrated light of galactic globular clusters as well as the models that are used to interpret their properties. Another area that is discussed is the infrared observations of clusters in the Magellanic Clouds, their interpretation, and how they differ from galactic globular clusters. We also compare the observations of all these with the trends shown by normal elliptical galaxies.

GOALS AND EXPECTATIONS

At the distance of M31, although the outermost parts of a few clusters have been resolved into individual stars, most observations of the globular clusters are observations of their integrated light. The parameters we can hope to determine are the fundamental ones describing the stellar population of the cluster, including metallicity, age, and luminosity function (i.e. slope of the IMF, for example). With extremely good data and models, one can hope to obtain information on such secondary parameters affecting the integrated light as the distribution of stars along the horizontal branch, etc.

With such information for an ensemble of clusters forming a globular cluster system around a galaxy, one can hope to attack such issues as the mean metallicity of the cluster system, the metallicity range and distribution, the variation of metallicity with galactocentric distance, and the luminosity distribution of the clusters. Here by "metallicity" we mean [Fe/H], or [Ca/H] (which presumably are related, although exactly how may not be known), or whatever element's lines are being used.

Comparison objects for extragalactic globular clusters include on the observational side the galactic globular clusters, and on the other hand the theoretical or semi-empirical synthesis models for the integrated light. In addition, since until recently it was believed that early type galaxies were similar in stellar population and star formation history to the globular clusters, in that both were residuals of a single large burst of star formation approximately 15 billion years ago, such early type galaxies are often compared to globular clusters.

There are two major cautionary remarks that must be made. The stochastic effects are larger in the infrared than at optical wavelengths. This is particularly serious for sparse clusters. The other point to bear in mind is that of biases due to cutoffs in the magnitude selection criteria at one wavelength or another for the sample of clusters.

OBSERVATIONS OF INDIVIDUAL STARS IN THE GALACTIC GLOBULAR CLUSTER SYSTEM

Frogel, Cohen, and Persson (1983) summarized the results of a long campaign to observe separate stars in galactic globular clusters in the infrared. They defined various characteristics of the giant branch of each globular cluster, specifically M_{K_o}, the absolute K magnitude of the mean giant branch at $(V-K)_0 = 3.0$, and the parameter $(V-K)_0$, the color of the mean giant branch at $M_{K_o} = -5.5$. They showed that $(V-K)_0$ and M_{K_o} increase linearly and monotonically with metallicity as measured on the Zinn (1980) scale. The same is true of measurements of the narrow band CO index for globular cluster giants. In other words, as expected from the theory of stellar evolution (see for example, the Yale tracks, Ciardullo and Demarque 1977, which have recently been updated in Green, Demarque, and King 1987), the giant branches of galactic globular clusters form a monotonic family of more or less similar curves in the (K, V-K) plane, with metallicity providing the parameter that ranks the clusters.

This is illustrated in figure 1, taken from Frogel, Persson, and Cohen (1980). In the top panel $(V-K)_0$ is plotted against [Fe/H] on the Zinn (1980) scale, while in the bottom one, the CO parameter characteristic of each globular cluster is plotted against [Fe/H]. Each point represents an individual galactic globular cluster.

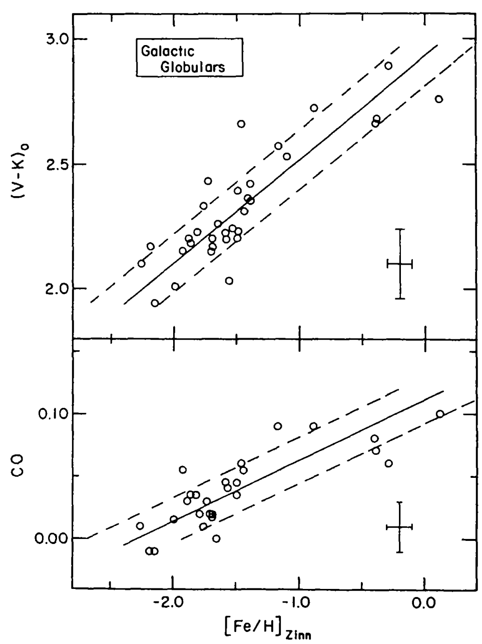

Fig. 1. The relationship between $(V-K)_O$, CO, and [Fe/H] for galactic globular clusters. The $(V-K)_O$ and CO values are from ACMM; the [Fe/H] values are from Zinn. Best fit least squares solutions and their $\pm 1\sigma$ residuals are also shown.

Another point of comparison with the theory lies in the luminosity of the brightest red giant, i.e. the luminosity of the He core flash. In practice this means the brightest non-variable K or M giant, as variable giants are probably second ascent asymptotic giant branch stars. Sweigart and Gross (1978) were among the earliest to make definitive predictions for the luminosity of the He core flash, and the observational data for a large sample of galactic globular clusters agrees well qualitatively and quantitatively with their predictions, with the luminosity of the brightest star increasing slowly as the cluster metallicity increases.

Frogel and Elias (1988) discussed the red variable stars in galactic globular clusters. They find the long period variables to have luminosities up to 1 mag brighter than the limit for first ascent red giants, and to be confined to the metal rich clusters.

In summary, the galactic globular clusters have a family of giant branches that become redder monotonically as the metallicity increases, in good agreement with the theoretical predictions. We can use this behavior as a key indicator to calibrate integrated light photometry of globular clusters.

MODELS FOR THE INTEGRATED LIGHT OF GLOBULAR CLUSTERS

A model for the integrated light of globular clusters can be constructed in principle by adopting a history of star formation (usually a single burst at a particular epoch in the past), and adopting a model predicting the relative number of stars at various locations in the stellar evolutionary sequences (giants, horizontal branch stars, main sequence dwarfs, etc), as well as the temperatures and surface gravities for each point on the evolutionary tracks. To this one adds a grid of predicted or observed stellar colors as a function of T_{eff} and surface gravity. The predictions of such a model include not only integrated colors, but also the evolution of integrated luminosity of the cluster at a particular wavelength, or bolometric luminosity, with time.

Among the earliest of such models was that of Aaronson et al (1978). It uses a single burst of star formation 13×10^9 years ago and the Yale evolutionary tracks, with the advanced stages of stellar evolution, i.e. the horizontal branch and the asymptotic giant branch added in. Grids of optical and infrared colors as a function of T_{eff} and surface gravity are also utilized. It was used to predict broad band colors from U to K, as well as the narrow band indices for CO and H_2O features in the infrared. The parameters are the metallicity and the slope of the initial mass function, with the horizontal branch being added more or less ad hoc, as its not included in the Yale tracks.

Figure 2 shows the comparison between the models, the integrated colors of the galactic globular clusters, and early type galaxies (the filled triangles). One sees that the models and the observations of the integrated light of the galactic globular clusters agree well from 0.35 to 2.2 μ over the full range in metallicity spanned by the clusters. The ellipticals appear to be even more metal rich than the highest metallicity clusters. But there is a problem in matching the light of elliptical galaxies. At a given (V-K) color, they are too blue in (U-V).

Interesting recent models can be found in Renzini and Fusi Pecci (1988), where the contribution to the integrated light of various evolutionary phases is shown as a function of age. As expected, red giants dominate the light from an old population, while the asymptotic giant branch dominates the light from an intermediate age population. Another interesting recent toy model is that of Frogel (1988), who adds in the luminous giants that were not properly taken into account in the earlier ACMM models.

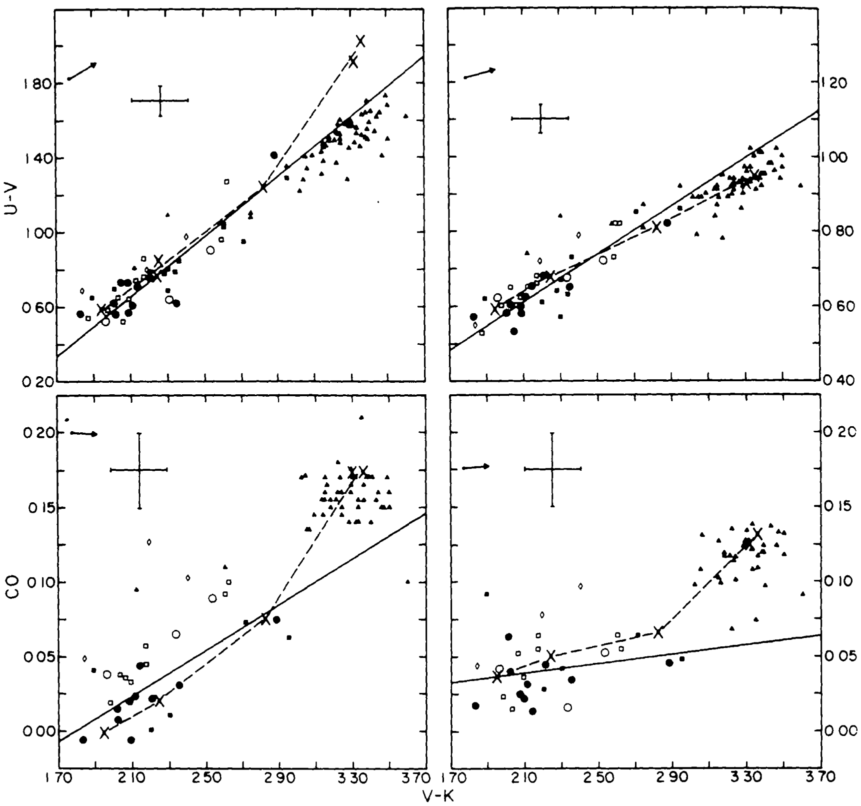

Fig. 2. Globular cluster $U-V$ and $J-K$ colors, and CO and H_2O indices, are plotted against $V-K$. Triangles denote early type galaxies. The model results with $s = 2.35$ are shown as crosses and are connected by the dashed line. The other symbols are galactic globular clusters with objects of the highest weight shown as filled circles. The least squares line has been fitted through all but those clusters with uncertain reddening and metallicity, weighting the low-reddening ones twice that of the high reddening ones.

THE CLUSTER SYSTEM OF THE MAGELLANIC CLOUDS

The first extragalactic globular cluster system studied in detail was the clusters of the Large and Small Magellanic Clouds. The pioneering work in the optical of Searle, Wilkinson, and Bagnuolo (1980) established that the populous clusters spanned a wide range in ages, from under 10^9 to $15\text{x}10^9$ years, the age characteristic of galactic globular clusters. The infrared analysis by Persson et al (1983) clearly established the difference in contribution to the infrared integrated light by different stellar evolutionary phases at different times.

In particular, the dominance of the carbon stars in the integrated light of the intermediate age clusters was clearly demonstrated, both by analysis of the (V-K) colors and more emphatically by considering the narrow band CO indices.

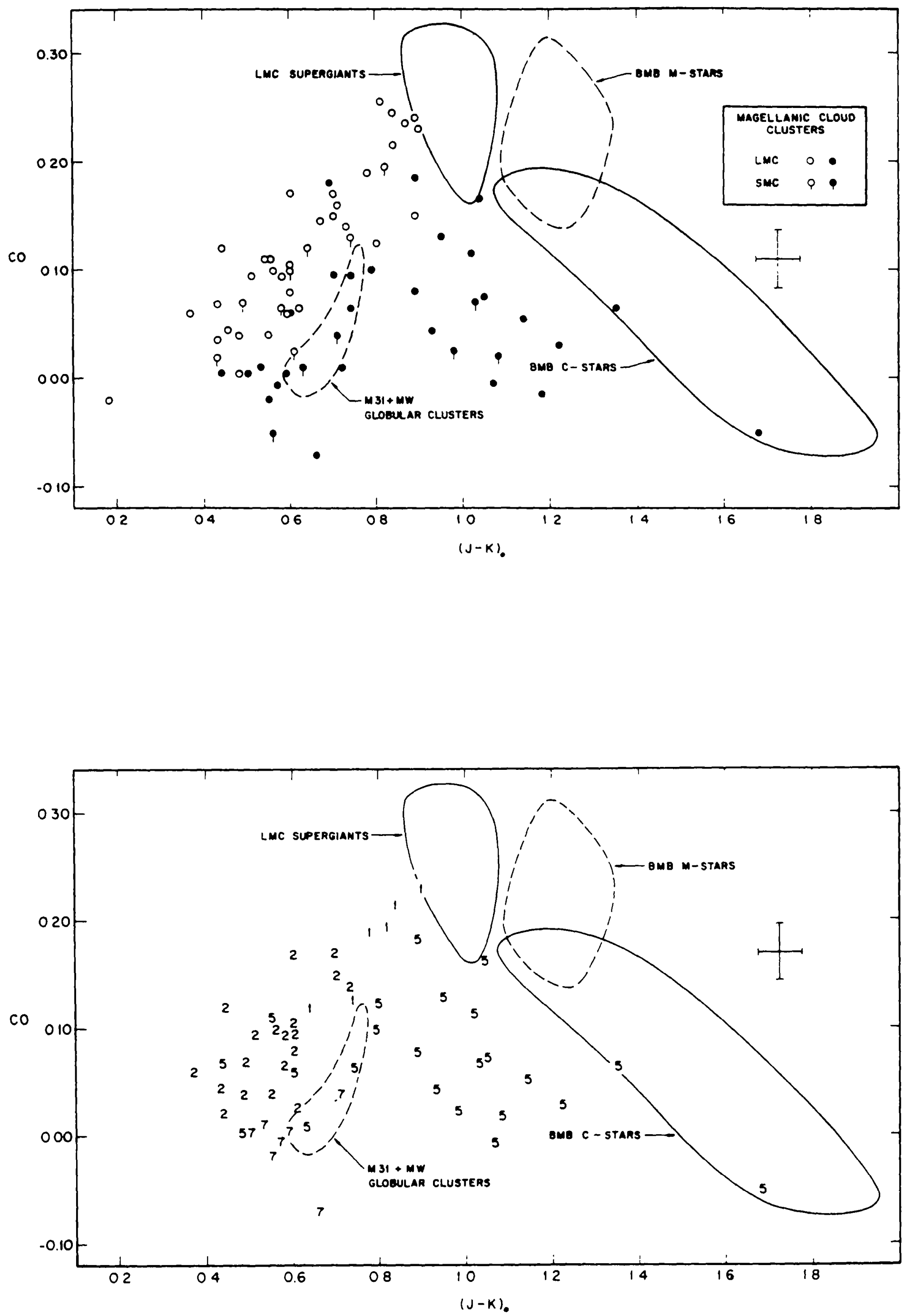

Fig. 3. The reddening-corrected CO index is plotted against $(J-K)_0$ for SMC and LMC clusters. The regions enclose most of the individual star and cluster data for LMC M giants and C stars, M31 and galactic globular clusters, and LMC supergiants. Figure 3b repeats figure 3a but with numbers referring to cluster data points in the following SWB groups: 1 = I, 2 = II and III, 5 = IV, V, and VI, 7 = VII.

The oldest clusters have infrared colors and indices which mimic those of galactic globular clusters. The infrared light of the youngest clusters is dominated by that of the red supergiants. Figure 3 shows this quite clearly.

GALAXY BULGES

Since globular clusters are believed to be old systems with a single burst of star formation, it behooves us to compare them with other systems we believe to represent old stellar populations, such as elliptical galaxies or the bulges of spiral galaxies. Frogel (1988) has summarized the comparison with infrared photometry of giants in Baade's windows in the nuclear bulge of the Galaxy. The bulge stars are obviously more metal rich than the globular cluster 47 Tuc, which is not surprising. What was initially surprising was the discovery that the bulge stars reach a luminosity up to 1 mag higher than the red giant tip in galactic globular clusters. Although it has been suggested that this indicates the presence of a component of younger stars, a more likely explanation for the high luminosities is the extension of the first ascent giant branch produced by the enhanced metallicities of the bulge stars. See Frogel (1988) for a more complete discussion of the various possibilities.

With the advent of ir arrays similar studies have become possible in the bulges of nearby galaxies. Rich and Mould (1991) analyzed data for the bulge of M31, and found stars extending in luminosity up to 1.5 mag brighter than the first ascent red giant tips. This is too much to be explained by enhanced metallicity. Among the possibilities discussed by them and others are a substantial contribution from younger M31 disk stars projected onto the M31 bulge, the presence of a small population of binaries, the presence of many luminous OH/IR stars, crowding effects, etc. A similar situation exists in the nuclear bulge of M32, where Freedman (1992) has found a similar excess of overly luminous stars, looking quite like the bulge of M31. There is no disk in M32, so at least that explanation can be ruled out there.

THE M31 GLOBULAR CLUSTERS IN THE INFRARED - PHOTOMETRIC OBSERVATIONS

The M31 globular clusters are tempting targets for infrared observing. They are bright (the brightest have K $\approx$ 12.5 mag), and they are only slightly resolved. Except for the nuclear clusters, where background subtraction is a serious issue, they are easy objects for single channel detectors, which were the only detectors in use in the infrared until recently. The studies of the infrared integrated light comprise 3 papers: Frogel, Persson, and Cohen (1980) observed 40 clusters, Sitko (1984) observed 16, of which 6 were repeats, and Bonoli et al (1987) observed 27 more, of which 9 had been previously studied. Thus the total sample of M31 clusters with infrared data is 68.

In the pioneering work of Frogel, Persson, and Cohen (1980), the narrow and broad band infrared colors and indices of the M31 globular clusters were compared to those of the galactic globular clusters and of early type galaxies. The M31 globular clusters appear to be good analogs of the galactic globular clusters, while the early type galaxies show the anomaly noted earlier. Namely, at a given (U-V) color, their (V-K) colors are unexpectedly red by ≈0.2 mag when compared to either the galactic or M31 globular clusters or the ACMM models. Figure 4 illustrates this, where the M31 globular clusters are denoted by the crosses, while the galactic globular clusters are shown as the open circles.

The narrow band indices (CO and H_2O) show the same behavior. The M31 and galactic globular clusters overlap, while the early type galaxies lie on an extension toward higher metallicity of the M31 clusters and the ACMM models.

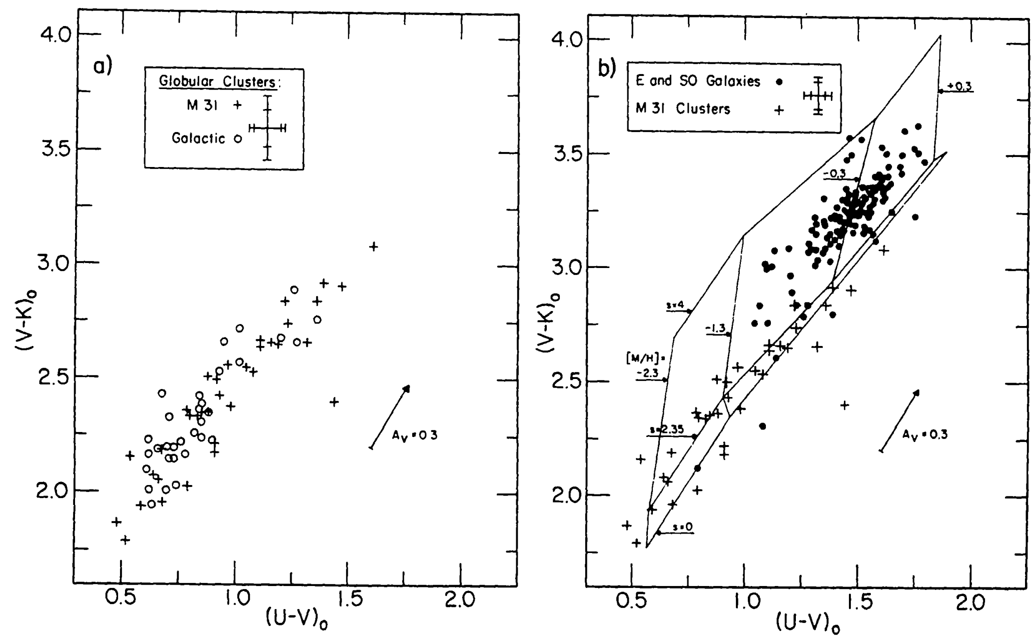

Fig. 4. (a) A $(U-V)_0$, $(V-K)_0$ plot for the M31 globular clusters and the galactic globular clusters (ACMM). Typical errors are indicated in the box. The outer tic marks are for the galactic globulars as given by ACMM; the inner ones are for the M31 clusters. (b) $(U-V)_0$ versus $(V-K)_0$ colors for early type galaxies and for M31 globular clusters. Fiducial lines for the models are superimposed.

The analysis by Bonoli et al (1987) uses the cumulative sample to determine the metallicity distribution of the cluster system. The mean metallicity is −1.28 dex, and there is no sign for a gradient in metallicity as a function of projected galactocentric distance. Figure 5 illustrates the comparison of the metallicity distribution determined from infrared observations as compared to that determined optically from Huchra, Brodie, and Kent (1991). Note that the mean is essentially the same, but Huchra, Brodie, and Kent (1991) claim that there is a radial gradient in mean metallicity. This difference probably arises because the most metal rich clusters are confined to the inner 2 kpc (i.e. the region of the M31 nuclear bulge), and none of these have as yet been observed in the infrared due to problems with background subtraction using a single channel detector. The sample with infrared data is biased toward the outer parts of M31. I have a program to observe these nuclear M31 globular clusters using an array detector where background subtraction should be straightforward.

Bonoli et al (1987) also noted that in a two color plot of $(U-V)_0$ versus $(V-K)_0$ the M31 globular clusters show slightly more scatter about the mean line than do the galactic globular clusters. This is likely to be due to the larger photometric uncertainties in the M31 data, and is probably not real.

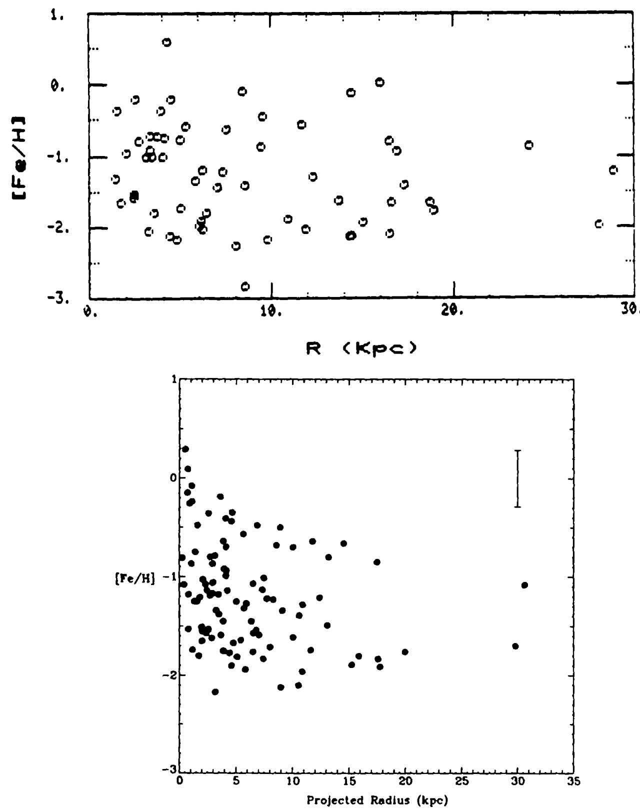

Fig. 5. The upper panel shows [Fe/H] deduced from the infrared color $(V-K)_O$ as a function of galactocentric radius for the combined sample of M31 globular clusters from Bonoli et al. The lower panel shows metallicities determined from optical spectroscopy of M31 globular clusters as a function of projected radius from Huchra, Brodie, and Kent.

THE M31 GLOBULAR CLUSTERS IN THE INFRARED - SPECTROSCOPY

There is one spectroscopic study of 4 M31 globular clusters by Davidge (1990) using a medium resolution Fourier Transform Spectrograph. He observed spectral regions in the near infrared with CN, CO, and C_2 bands of 4 M31 globular clusters, summed them up to improve the signal-to-noise ratio, and compared the sum to spectra of metal rich and metal poor galactic globular clusters. He found strong enhancements of CN in the summed spectra of the 4 M31 globular clusters, even when compared to spectra of metal rich galactic globular clusters. Figure 6 shows a section of the spectra.

Since the C_2 bands are normal, the enhancement of CN must be due to an overabundance of N. This is similar to what is seen from optical spectra of the M31 globular clusters, where there are several CN features, as well as the G band of CH, but no bands of C_2 or CO, by Brodie and Huchra (1991).

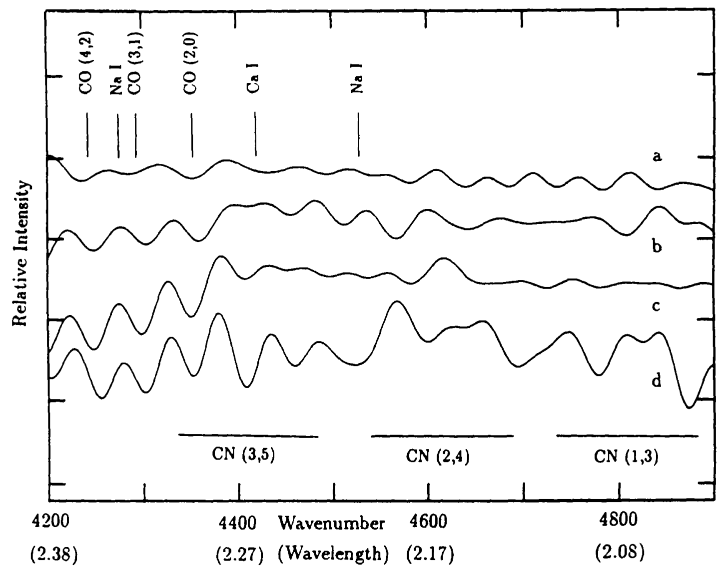

Fig. 6. The mean spectrum of four M31 globular clusters in the interval 4200–4800 cm^{-1} from Davidge compared with a mean spectrum of galactic metal poor clusters (curve a), and the galactic metal rich cluster NGC 6316 (curve b) and NGC 6304 (curve c). The position of each CO bandhead is marked. The horizontal lines indicate the approximate extent of CN absorption features.

SUMMARY

The M31 globular cluster system is a family whose properties, as measured by photometric observations of the integrated light at optical and infrared wavelengths, are indistinguishable from those of the galactic globular clusters. The M31 globular clusters overlap the galactic globular clusters in spectral energy distribution from 0.3 to 2.2 μ. Their broad and narrow band colors are to first order determined by metallicity only. They fit the ACMM models with an initial mass function whose slope is that of the Salpeter value or less. Dwarfs do not contribute significantly to the integrated light in the infrared.

As inferred from broad band colors, the mean metallicity of the M31 globular cluster system is –1.28 dex. There is no obvious gradient of [Fe/H] within a projected radius of 20 kpc. One should note that the nuclear globular clusters in M31 have not been observed in the infrared due to difficulties with background subtraction, a situation that should be remedied shortly now that infrared arrays are widely available.

At a fixed $(V-K)_0$ color, the $(U-V)_0$ colors of the M31 globular clusters show a slightly larger dispersion than do galactic globular clusters. This could be due to an intrinsic effect, perhaps a larger variation in the morphology of the horizontal branch at a given metallicity, or to the effect of an observational problem, for example reddening variations or larger photometric errors in the M31 data. I believe the effect is not real, but only future work can confirm this.

Early type galaxies are significantly redder in $(V-K)_0$ at a fixed $(U-V)_0$ and have somewhat stronger CO and H_2O indices than do either the M31 or the galactic globular clusters. The early type galaxies need an additional cool luminous stellar component, which might be very metal rich stars or luminous asymptotic giant branch stars, beyond those present in even metal rich galactic globular clusters contributing to their integrated light.

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